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Acoustics of Shallow Water: A Status Report

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This report summarizes the present state of knowledge of acoustic propagation, including reverberation, as it applies to ASW in shallow water. It also identifies key experiments upon which this knowledge is based, and summarizes the status of environmental data bases and environmental acoustic models that would be used for acoustic forecasting or system performance prediction. Corresponding long range R&D goals, and basic issues that need to be resolved, are identified.

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ACOUSTICS OF SHALLOW WATER: A STATUS REPORT

I. INTRODUCTION

This paper is intended to define the present state of knowledge of acoustic propagation, including reverberation, as it applies to ASW in shallow water. Numerous in-depth reviews already exist that describe the theoretical and experimental background of shallow water acoustics, and it is not intended to repeat that extensive material here. The present paper is directed toward summarizing the present conceptual understanding of acoustic signals in shallow water, the extent of relevant data, and the status of modeling and prediction. It also defines long range technical goals for a research program in shallow water acoustics that addresses Navy problems, and identifies key environmental issues and some measure of the progress that has been made. The paper is intended for use as a basic reference document for the evaluation and planning of EVA research in this area.

II. UNDERLYING CONCEPTS

Out of the process of comparing experimental observations to theoretical predictions over the past several decades, a conceptual picture has emerged of the acoustics of shallow water and of the important environmental characteristics that influence it. This conceptual picture, as described below, is a concensus of community views. The utility of constructing such a view is that it provides a conceptual framework against which future observations or predictions can be compared. If the underlying concepts are correct, then new observations are more readily anticipated and understood.

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The underlying conceptual picture of the acoustics of shallow water as it affects ASW sonar operation is this:

The manner in which the sound speed profile influences signal propagation, the mechanisms that degrade signal coherence, and the scattering at rough boundaries are essentially the same in shallow water as in deep water. What distinguishes these two regions is mainly the relatively greater role played in shallow water by reflecting and scattering boundaries. Furthermore, differences from one shallow region to another are driven primarily by differences in the structure and material of the ocean bottom. Thus, in shallow water, the ocean bottom is perhaps the most important part of the environment that differentiates between different regions.

The most prevalent shallow water environment has a sand or silt sediment bottom whose sound speed exceeds that of water. Acoustic signals that strike the bottom at sufficiently small grazing angles are nearly totally reflected back into the water. In such a region the water column acts as a slightly lossy waveguide in which energy is trapped and can propagate to long ranges. At low to middle frequencies (e.g. 100-1500 Hz), signal attenuation is caused primarily by cylindrical spreading, by absorption within the water itself, and by losses resulting when the signal strikes the bottom. Reflections from the bottom and surface are sufficiently coherent in space and time, at least for low to middle frequencies, to support the formation of a modal structure of the acoustic field. The field penetrates the bottom sediment to a depth that is proportional to the wavelength. The acoustic losses at the bottom are caused by various attenuating mechanisms such as compressional wave absorption in the sediment and conversion of part of the incident energy to shear waves. Roughness of the ocean surface and bottom are perturbing effects that increase attentuation by causing more energy to be directed into the bottom.

At very low frequencies (e.g. below 100 Hz), the field can extend a substantial distance into the bottom. Subbottom layering can then have significant influence on the losses and group velocities of separate modes and can be a significant EVA parameter. In addition, low frequency energy that penetrates the bottom can be returned to the water column by subbottom reflections or subbottom upward refracted paths.

At higher frequencies signals reflected from the boundaries become less coherent spatially. The modal character of the field is less apparent, and ray paths are a useful representation of the field. Losses at both boundaries tend to increase with frequency. Subbottom structure is not of concern at higher frequencies, and bottom-reflected signals involve only the surficial sediment layer. Irregularities of ducts within the water column become controlling parameters.

The reverberation intensity at any instant is the total of contributions by all round trip paths from source to receiver, arriving simultaneously from each differential scattering area or volume element. The scattering intensity from a differential element is proportional to the incident intensity and may depend also on the angles of incident and scattered energy. The scattered intensity from any single path is sufficiently small that second-order scattering (secondary scattering of previously scattered sound) is negligible. Scattered returns from separate scattering areas are uncorrelated. Crosspath contributions to the total reverberation level are significant and must be included in predictions. Reverberation levels can be predicted by summing all contributions based on a knowledge of propagation path structure, bathymetry, and the appropriate scattering strengths.

Bottom scattering results both from the water-sediment interface roughness as well as from inhomogeneities within the sediment. The degree to which scattering comes from either the interface or the underlying sediment volume is not presently known, and no comprehensive theory of backscatter is available to resolve this issue.

III. GENERAL DISCUSSION OF ENVIRONMENTAL EFFECTS

The following discussion of environmental effects is approached in order of increasing complexity of the field, beginning with signal power (as would be measured with an omnidirectional sensor), considering next the space and time structure of the signal, then considering higher order effects of coherence and fluctuations, and ending with the reverberant field.

A. SIGNAL ENERGY

1. Cylindrical Spreading

The conceptual picture of the shallow water channel as a slightly lossy duct has several implications. For example, one characteristic of propagation in a ducting environment that helps distinguish shallow water from deep water environments is the dominance of cylindrical spreading of energy. A signal confined to a duct undergoes the usual spherical spreading for only a short distance and then tends to spread cylindrically as the effects of vertical confinement become apparent. At long ranges, the relatively close proximity of the lossy boundaries leads to greater losses that counter the effects of confinement and become the dominant form of attentuation.

The tendency toward cylindrical spreading is illustrated by Fig. 1, which shows 1/3-octave-band propagation loss data at a center frequency of 200 Hz as a function of range. An omnidirectional hydrophone in this experiment was located at a depth of 91 m in water approximately 210 m deep, and the sources (explosive charges) were set to detonate at a depth of 91 m along a track whose total water depth gradually dropped from about 220 m to 300 m, for the portion of track represented in the figure. The sound speed is approximately constant, and the bottom sediments are reported to be silty-sand near zero range and sand-silt-clay at greater ranges. Propagation loss was determined by integrating the pressure-squared over the duration of the signal. Figure 1 also shows reference curves for spherical spreading and for cylindrical spreading beyond 1 km. The data show that acoustic energy is effectively trapped by the waveguide at ranges less than about 40 km. Accumulated effects of bottom losses become apparent beyond 40 km, as the data drop noticeably below the cylindrical spreading reference curve.

The observed fluctuations in the data are believed caused by phase interference. Narrow band signals would show far greater variability. The use of third-octave filtering at 200 Hz tends to smooth out the variation, but the bandwidth is not sufficiently broad to produce an entirely smoothed curve. Because of the substantial amount of energy reflected from the boundaries, shallow water channels generally do not have pronounced shadows or convergnce zones of the sort that are common in deep water. The tactical significance of such a result is that one can anticipate fairly uniform range coverage of broadband detections.

2. Channel Bandwidth

Another implication of the waveguide picture of shallow water propagation is that there should be an optimal frequency at which propagation loss is a minimum. As frequency decreases below the optimum, the propagation loss increases because the modal sound field is forced to strike the bottom at increasingly steeper grazing angles. Propagation is ultimately limited at low frequency by waveguide cutoff effects that result from the inability of the duct to trap low frequency energy. In shallow water low frequency signals suffer rapidly increasing losses to the bottom as cutoff is approached, and the frequency that gives strongest propagation can be several octaves higher than the cutoff frequency inferred from ideal wave guide theory. Ducted signals suffer increased losses also at high frequencies, resulting from absorption in the water and from scattering losses at rough boundaries.

Two measured examples [1,2] of a transmission loss passband and optimal frequency are shown in Fig. 2, for two different geographical regions. These particular examples were selected to reinforce the idea that although the general passband character is common to many shallow water regions, the actual frequencies at which the peaks occur can vary substantially.

3. Bottom Influence On Long Range Propagation

The structure and properties of the ocean bottom are dominating environmental influences that control whether low-and mid-frequency signals can or cannot propagate to long range. It is true that in some cases upward refracting conditions in the water will prevent any significant influence of the bottom and allow long range, low loss propagation. When shallow water signals are rapidly attenuated, however, it is usually because of the bottom, except for high frequencies where sea water absorption becomes important. The remainder of this section summarizes the basic bottom properties that have been observed to have a significant influence on the attenuation of signals in shallow water.

Sediment type. The results of extensive propagation loss measurements from 100 to 2800 Hz at stations along the east coast of the U.S. [3] have been summarized by classifying the entire region on the basis of two bottom types, mud or sand. Typically for these data mud bottoms resulted in greater losses than did sand bottoms.

Fast sediments. Sand, like silt, is an example of a high-speed bottom in which the sound speed is appreciably greater than that of water. For low grazing angles most of the energy of signals incident on the bottom is reflected, and the slight losses that do occur generally are the result of absorption within a relatively thin penetration layer in the top part of the sediment. Except at very low frequencies, subbottom returns play only a minor role, and detailed knowledge of the subbottom structure is not critical. The primary environmental input is the sound speed profile within the water, which is readily measureable.

Broadband (1/3 octave) propagation in fast-bottom shallow water regions has been modeled successfully in a number of cases. A recent noteworthy comparison of data with prediction was carried out by Jensen and Kuperman [4,5] and is illustrated by Figs. 3a and 3b in Ref. 4. The data agree well with model results. Another example in which qualitative features of broadband propagation losses appear to be well understood for a fast-bottom region in shallow water is due to Wakeley [1], illustrated by Fig. 4 of Ref. 1. It can be concluded that propagation mechanisms and their relation to bottom properties are qualitatively well understood for fast bottom, sand or silt regions.

Remaining technical issues for fast bottom regions are

- How to quantify the effects of a rough boundary.
- To what extent do bottom losses result from conversion of water borne energy into shear waves at the bottom.
- What is the frequency and depth dependence of acoustic absorption within the sediment.

Slow sediments. Slow bottom, mud regions offer greater challenge for two reasons. First, low frequency energy will be returned both by reflections at the interface as well as by diving, bottom-refracted or subbottom reflected waves. The properties of such deep refracted waves are qualitatively understood for single bounce deep water conditions, but their implications in shallow water, especially in connection with short range caustics and signal vertical directionality, have been largely ignored by the preponderance of smoothed, long range propagation studies. Second, the quantitative aspects of the bottom-refracted component can be extremely sensitive to relatively small changes in the sound speed structure within the bottom, thus making accurate prediction unlikely. Slow bottom regions are inherently more difficult to model by ray trace techniques because two forms of bottom return must be considered.

Some examples do exist however in which careful geophysical measurements of the bottom properties have led to satisfactory understanding (as demonstrated through modeling agreement) of the data. One of these is by Rubano [2]. The geoacoustic model for his experimental region and measured and calculated transmission spectra at fixed ranges are shown in Fig. 3. The rapid rise in propagation loss above 200 Hz is attributed to the thin, slow top layer of sediment. At this and higher frequencies the slow layer acts as an internal duct itself and attenuates the otherwise water borne signal by a form of resonance absorption.

Another example of successful modeling of the influence of a slow bottom layer is provided by Jensen and Kuperman [5]. A 6-m-thick slow layer, as in Fig. 4, is responsible for relatively low loss at 50 Hz but relatively higher loss at 3200 Hz. The influence of the slow layer is significant, as indicated by the authors in their statement,

> "...the agreement is good for the two widely-different frequencies (50 Hz and 3.2 kHz), an agreement that could not have been obtained using an over-simplified homogeneous bottom as input to the model."

B. ARRIVAL STRUCTURE

A primary characteristic of acoustic signals in shallow water is their multi-arrival structure. Portions of the total signal arrive over several separate paths, at several vertical angles and times. The complexity of the arrival structure, whether viewed in angle or time, is generally not apparent in measurements of propagation loss that emphasize the total energy of all arrivals. The arrival structure can be expressed either in terms of ray paths or normal modes; the normal mode picture is more convenient at lower frequencies however.

1. Discrete Modal Character

Low and mid frequency fields at moderate to long ranges from the source can be represented as a sum of a relatively small number of discrete modes, each having a characteristic structure and propagation speed. Ferris [6] employed a vertical string of hydrophones to identify and resolve individual modes involved in the propagation of a pulsed CW signal in shallow water. His success in the experiment provides a convincing demonstration of the basic reality of modal propagation.

2. Frequency Dispersion Effects Of The Ocean Bottom.

Another result of the waveguide nature of shallow water channels is that the spectral content of a pulse is spread in time as each frequency component propagates at its own characteristic speed. Dispersive propagation in ducts is conveniently described in terms of normal modes. Generally, each mode in the duct has both a phase velocity and a group velocity that vary with frequency, and for each mode, separate frequency components will arrive at separate times. The dispersion properties of the duct are represented by the set of curves that give group velocity for each mode as a function of frequency.

For rather simple shallow water environments, where the sound speed in the water is essentially uniform and the underlying sediment has a sound speed greater than that of water, as illustrated at the top in Fig. 5, the dispersion curve for a single mode (group velocity vs frequency) takes the form sketched in the lower part of that figure.

Below a certain frequency the group velocity increases and approaches c_2 as shown in Fig. 5. For this case the lower frequency signals penetrate deeply into the faster bottom. The close agreement that has been documented between analytic and observed dispersion curves like that in Fig. 5 represents perhaps the strongest building block in our knowledge of shallow water acoustic propagation. The single document most responsible for advancing this knowledge is the work by Pekeris [7].

Further studies by Pekeris show that added layers in the ocean bottom can cause further variations in the dispersion curve. Possibly the most significant aspect of the dispersion curves is that they can serve as a fingerprint to help identify features of the subbottom which then can be used to further classify the acoustic properties of a region and to support acoustic predictions.

Dispersion effects are most pronounced at low frequency, and their influence on ASW system performance is not clear. It is conceivable, however, that they could exert an adverse influence on broadband time delay estimation or on active echo ranging.

The presence of dispersion can cause an initially short-duration signal to be stretched in time. Figure 6 is a sketch of some results reported by Tindle, et.al. [8] that demonstrate time stretching of an initial four-cycle pulse in 50-m-deep water, at a range of 5 km. At 60 Hz only one mode exists; it is highly dispersive, and the pulse is stretched from an initial duration of approximately 67 msec to a duration of roughly 150 to 200 msec, depending on where one considers the pulse to end. The signal at 100 Hz stretches from an initial duration of 40 msec to approximately 130 msec, and now consists of two modes. Hence, the pulse experiences time stretching by both dispersion and multipath propagation.

C. HIGHER ORDER EFFECTS

1. Coherence and Spreading

Coherence of the field means there is some degree of stability or predictability of the phase of a signal at different times or locations. Measurements of coherence involve the correlation of a signal either with a modified version of itself or with another signal. The signal itself typically is a function of time and space or, through transformation, of frequency and angle. Consequently, correlations can be formed in a variety of ways. Associated with each correlation is a corresponding spread such that a high correlation in one variable corresponds to a small spread in a corresponding variable. A list of several possible correlations and corresponding spreads is presented in Table 1, along with the identification of a possible application, if any, associated with each example.

Two correlations especially of interest in underwater applications, and about which something is known in shallow water, are

i) correlation of a signal with a sinusoid, and

ii) correlation of band limited, time shifted signals at two separate locations.

The first case above pertains to the extraction of narrow band tonals from a noise background. In a motionless environment, tonal signals may be integrated coherently for long times to yield high signal to noise ratios. Effects such as target-receiver motion, a changing medium, or interaction with a dynamic sea surface, however, will create instability of phase, broaden the tonal spectrum, and establish an upper limit on the time for which coherent integration is feasible.

Table 1*

SPECIAL CASES FOR CORRELATIONS

Correlation	Spread	Relevant Application
Temporal correlation for particular location	Frequency spread	Line detection for single sensor
Spatial correlation for particular time	Angular spread	Broadband cross-correlator
Temporal correlation for particular angle	Frequency spread	Line detection on a beam
Spatial correlation for particular frequency	Angular spread	Narrowband beamformer
Frequency correlation for particular location	Temporal spread	Harmonic correlation for single sensor
Angular correlation for particular time	Spatial spread	-
Frequency correlation for particular direction	Temporal spread	Harmonic correlation for a beam
Angular correlation for particular frequency	Spatial spread	-

*This table was compiled by J. S. Hanna of Science Applications, Inc., under contracted technical support.

The spectral spreading of a CW signal propagating through an acoustic channel of moderate depth was examined by Veenkant [9] based on measurements across the so-called MIMI channel in the Straits of Florida. Part of the propagation was effected by a surface duct. For this surface channel, the received spectrum showed that the transmitted 420 Hz CW tonal was spread a few tenths of millihertz by long term effects such as internal waves and tides and that two additional bands of energy appeared on each side of the CW line because of interaction with the surface. The total frequency spread was 0.6 Hz. Measurements by Roderick and Cron [10] of forward-scattered sound in a single interaction with the surface (not in shallow water) showed a similar spectral spread of energy for a variety of sea conditions. The observed side band frequencies are related to the sea surface spectrum, and in all observed cases the total frequency spread was less than 1 Hz. It is tentatively concluded for shallow water that the primary environmental cause of frequency spreading is interaction with the sea surface.

Mackenzie [11,12] measured spectral spreading of CW signals during long range propagation in two shallow water environments, one 60 fathoms deep with a sand bottom, the other 50 fathoms deep with a sandstone bottom. The results show a spectral spread proportional to the carrier frequency with a spectral slope symmetrical about the carrier and dropping off on each side as $(f)^{-3}$, where f is the frequency separation from the carrier. (Other data are fit better with spectral slopes proportional to the −2 or the −4 power.) The spreading was approximately twice as great for the sand bottom as for the sandstone bottom, but it is not clear whether this difference results from different sea conditions (seas were rougher during the sandstone measurements) or from differences in sound speed profile or bottom properties. Bandwidths of the spreading were generally less than 0.5 Hz.

The second correlation identified above is involved when an array of two or more sensors is used to form beams for the purpose of extracting discrete angle arrivals from a continuous (in angle) noise background. In the ideal medium, signals at separate hydrophones differ only by a delay time that can be adjusted to align the signals for a maximum signal-to-noise ratio. Typically in shallow water, however, several environmental effects disrupt the ideal condition. Primary causes of decorrelation are considered to be

1) multipath arrivals with a spread of vertical arrival angles,
2) interaction of the signal with rough boundaries, which generates azimuthal spreading of the arriving signal, possibly frequency dependent, and
3) dispersive effects, important for broadband processing, which give rise to frequency-dependent propagation speeds such that different delay times are needed to align the array at different frequencies.

For a horizontal array situated broadside to the arriving signal, only the second cause of decorrelation applies. Measurements in the North Sea [13] and in the Mediterranean [14] of the correlation between band limited signals (200 Hz band width) received at hydrophone pairs of various transverse separations showed that coherence decreases with increasing separation, and that higher frequencies decorrelate more rapidly than do lower frequencies. In the Mediterranean a higher degree of coherence was observed under isothermal winter conditions than under downward refracting summer conditions. Furthermore, observed coherence was substantially higher in the Mediterranean than in the North Sea. However, aside from differences in experimental geometry, the North Sea data were taken under heavy seas, and the Mediterranean data under calm seas. Azimuthal angle spreads in the Mediterranean were typically less than 1°. The effect of bandwidth was not examined in these measurements.

These results imply that a leading cause of signal decorrelation is its interaction with the rough sea surface. Numerous measurements have been reported describing coherence of single bounces of a signal at the surface. A remaining question that needs to be addressed is how the shallow water channel modifies the single bounce results to give corresponding results from multiple interactions with both upper and lower boundaries.

2. Fluctuations

The term fluctuations is used here to indicate the time variability in acoustic signals observed over time periods of tactical interest, from a few seconds to several minutes. Inasmuch as two dominant characteristics of shallow water acoustics are multipath and repeated boundary interaction, it follows that the two dominant sources of time variability are 1) motion of source or receiver through an otherwise stationary interference field, and 2) modulation of the interference field by time dependent mechanisms such as tides or surface waves. Urick [15] found narrow band signal fluctuations in deep water to belong to a class of Rician distributions. The governing environmental requirement for such a distribution is the presence of multipath, regardless of water depth; hence the Rician, or modified Rayleigh, distribution should apply in shallow water as well as in deep.

Mackenzie [11] compiled statistics of pressure amplitude values for CW propagation in shallow water. The resulting histograms confirmed Urick's findings that large amplitude variations can be anticipated and showed also that in many of the cases, the distribution deviates substantially from the Rayleigh distribution.

When comparing measured and predicted values of propagation loss against range, it is customary to look at smoothed values, basing the comparison only on long range trends. Comparisons would be more informative and more convincing if the interference effects were included and if comparisons were based on the details, not only on smoothed trends. An example of such a comparison [16] is shown in Fig. 7. For propagation in shallow water (approximately 110 yds deep with a surface duct down to 65 yd) the theoretical calculations indicate that the long range propagation is dominated by two ducted modes whose interference causes the beat pattern indicated. The approximate agreement with the data at the longer ranges supports the theoretical picture and supports the general contention that the wide scatter in the data is caused at least in part by deterministic, modelable interference effects.

D. REVERBERATION

Reverberation, whether in deep or shallow water, is a combined result of backscattering and propagation and, hence, will have the environmental dependence of both these parameters. Backscattering from the ocean bottom shows great variability and is a cause of substantial geographically-related differences in acoustic response, far more so than is scattering from the surface. A measure of the scattering ability of the ocean bottom is its scattering strength S per unit area, expressed in dB/yd^2, and defined as

$$S = 10 \log (I_s/I_i),$$

where I_i is intensity incident on the scattering area and I_s the intensity of the scattered field, corrected to a reference distance of 1 yd.

Sediment type is one of the key parameters [17, 18, 19 and 20] that influences the bottom scattering strength, with gravel being the strongest scatterer, and sand, silt and clay being weaker. The scattering strength of the bottom also depends on angle, and the functional form generally assumed for this dependence is Lambert's Law, which is written in the NISSM II model [21] as

$$I_s/I_i = \mu \sin\Theta_i \sin\Theta_s \qquad (1)$$

where Θ_i *is the grazing* angle of the incident wave on the scattering area element, Θ_s is the grazing angle at which the scattered field is measured, and μ is a scattering coefficient expressed in dB/yd^2. (An alternative to Lambert's Law is the omnidirectional relation

$$I_s/I_i = \mu \sin\Theta_i \qquad (2)$$

in which the incident flux is assumed to be scattered uniformly in all directions. Data have been reported in support of both of these scattering laws.) Out-of-plane scattered intensity is independent of azimuth [22], and the scattering strength of the ocean bottom is practically independent of frequency [17,18] over a broad range of frequencies (e.g. 2-100 kHz in Ref. 18).

Extensive data for shallow water reverberation level as a function of range or time have been obtained. An example of a (monostatic) reverberation return is shown in Fig. 8 for the environment in Fig. 9 [23]. This example was chosen in order to illustrate the variability of the reverberation in range and the especially dramatic effect of the rocky patch. Each of the data points in Fig. 8 is an average for 10 pings.

Reverberation level is highly sensitive to properties of the bottom and, consequently, can have a strong dependence on azimuth about the projector. Examples of reverberation levels seen at different bearings from the same location [24] are shown in Fig. 10.

Reverberation level generally is correlated with propagation loss in the sense that regions of low loss tend to have high reverberation. Figure 11, based on data from the four shallow water stations of FASOR I [25], shows the general correlation between propagation loss and reverberation levels (normalized for 0 dB source level) for a range of 40 kyd. The three straight lines give the locus of values that would yield equal echo and reverberation levels, for the specified values of target strength TS, according to the relation 2 TL = TS-RL. Although the lowest propagation loss was observed at Station 7, the highest percentage of echo detections against a reverberation background was obtained at Station 10.

Reverberation levels in shallow water are often observed [25,26] to decrease at the same rate as, or faster than echo level, so that the echo-to-reverberation level either stays constant or increases slightly with range. As a result limiting range detections by active sonar in shallow water are made against a background of noise rather than reverberation.

During bottom bounce sonar operation in deep water, bottom reverberation is generally not a cause of limited performance because bottom reverberation from the main lobe has tapered off by the time of the target return. In that case reverberation from the sea surface in the vicinity of the target is the main source of interference background. In shallow water, bottom reverberation does not decay as rapidly as in deep water and, thus, can have a greater influence on active sonar performance. Furthermore, reverberation from the surface and from the bottom in shallow water generally cannot be resolved and separated in time.

Tests have shown that reverberation levels can be effectively reduced through the use of FM pulses [25] to achieve greater resolution in range. The results are environmentally sensitive however. Results in some areas show near ideal decrease in reverberation with increasing sweep rate (higher resolution), whereas less improvement has been noted in other cases.

1. False Contacts

False contacts during active sonar operation in shallow water create an especially severe problem. Obvious sources of false contacts are fish, bottom debris and shipwrecks. False contacts can result also from side lobe reflections. Low level side lobes directed toward the bottom or surface and specularly reflected back to the sonar can create a false target comparable in amplitude to real target echoes coming from some distant range. Because of this form of false contact, acoustic localization performance often is better in regions of high bottom loss than in lower loss regions. Because of the confusion and data overload presented to the operator by reverberation clutter and false contacts, it has been noted in operations (Ref. 27 p. 34) that sonar performance can be improved in a reverberation-limited environment if sonar power is reduced, after initial detection, in order to reduce clutter.

A false contact can be generated also from caustics that intersect rough boundaries in upward or downward refracting channels.

2. Reverberation Fluctuations

The deleterious effect of fluctuations in background interference (either noise or reverberation) is that their presence means greater signal-to-background ratios will be needed for detection in order to keep the false alarm rate down. It has been reported from operator experience (Ref. 27 p. 26) that background fluctuations are more severe and less predictable in shallow water than in deep water because of the close proximity of the scattering boundaries and also because acoustic parameters are generally more variable than in deep water. Fluctuations like those in Fig. 8, other than the peak attributed to the rocky patch, can result from coherent phase interference of direct and surface-reflected reverberation returns. The use of FM signals can help to smooth out fluctuations caused by phase interference. Similar phase-related interference fluctuations can result from differential doppler shifts in the reverberant signal that occur during use of active sonar from a moving platform [28].

IV. STATUS OF ACOUSTIC PREDICTION, MODELS, AND DATA

A primary need for research and development in shallow water acoustics, as related to ASW, is to characterize the environmental influences on propagation and reverberation in sufficient detail to support (1) the engineering design of sonar systems for use in a variety of environments that includes shallow water, and (2) the operational deployment of sonar equipment in arbitrary shallow water regions of the ocean. This support is to be provided, in general, through the development and use of numerical models, based on the underlying physics, that simulate the acoustic response of systems in various environments. When dependable physics-based models are not available for particular environments, as is believed by many to be the present case for shallow water, then empirical results of propagation loss against range and of reverberation level against time may be used. The major difficulty encountered in modeling the acoustic response of specific geographical areas is in identifying the relevant environmental parameters and obtaining suitable values of these parameters.

A necessary first step in obtaining models for engineering and operation support is to conduct a thorough study of the basic physics that underlies propagation and reverberation and of the associated environmental influences. This research effort entails the collecting of extensive data of propagation loss and reverberation and also requires having a variety of sophisticated research models to help deduce, from the data, the basic influences of the environment. Present status in this phase of effort is that an impressive collection of sophisticated research models has been developed. References 5 and 29 are two examples that demonstrate the commendable scientific progress that has been made in the modeling of acoustic propagation. The result of basic research over the past ten to twenty years has been a convincing demonstration that shallow water acoustic propagation at low to mid-frequencies is both understandable and modelable for a wide variety of environments, provided a sufficiently accurate representation of the environment, especially the bottom, is available. Thus, the problem of prediction lies not in the validity of the acoustic models but in the general lacking of adequate EVA inputs. The EVA input most crucial to propagation prediction is a measure of bottom related losses, which in general is not available for shallow water on a world wide basis. Possibly the most important parameter related to bottom loss is the sediment plane wave attenuation coefficient. The prevailing belief is that the attenuation coefficient depends primarily on sediment type and that a map of surficial sediment type could be converted ultimately to a map of bottom attenuation coefficient. The attenuation coefficient, however, depends also on depth and possibly on the age of the sediment and furthermore, bottom loss can depend also on the properties of deep sediment layers. Consequently, a data base for shallow water acoustic attentuation or bottom loss still lies out of reach.

The present status of reverberation prediction and modeling is less well developed than for propagation loss. One reason is that reverberation calculations require a more detailed accounting of propagation on a path by path basis than is required for estimates of propagation loss. A more significant problem, however, is the lack of an adequate supporting data base for bottom scattering coefficients. Values of the bottom scattering coefficient are needed either as a function of geographical location or as a function of bottom parameters such as sediment type. The scattering coefficients are derived from measurements of reverberation, coupled with various assumptions about the scattering law, the acoustic propagation, and the environment. A significant difficulty in obtaining these values is that unless the assumptions used in extracting the scattering coefficients from the received reverberation are very carefully chosen, the resulting coefficients will not represent valid environmental parameters, independent of how the data were obtained and analyzed.

Currently used engineering prediction models, such as NISSM II [21], for active sonar performance at frequencies typically from 1 to 10 kHz compute bottom reverberation by means of ray tracing coupled with Lambert's law for scattering at the bottom interface, as given by Eq. 1. No generally accepted data base is available for the scattering coefficient in shallow water, and consequently, Mackenzie's value

$$10 \log \mu = - 27 \text{ dB/yd}^2$$

is used for all regions as a form of default condition.

Because most sonar support models use the Mackenzie relation, differences in reverberation predictions by the various models arise primarily in how the propagation loss is computed on a ray by ray basis. (No attempt is made here to compare computational details of the separate models. Some information along this line can be found in Ref. 30). One important difference between models has to do with whether or not crosspath contributions are included. Crosspath contributions (reverberation that returns to the sonar by a path other than that followed by the incident energy) can represent a substantial part of the total reverberation and should be included.

Valid measurements of the backscatter coefficient in shallow water at sonar frequencies are difficult to obtain. Some indication of the spread in values that are available is found in results derived from the FASOR program [24]. Values of scattering strength for various angles are shown in Fig. 12, based in part on Fig. 21 of Ref. 24. In presenting scattering strength against angle it is conventionally assumed that the incident and scattering angles are the same. For data in Fig. 12 it was further assumed that the backscatter at each range may be regarded as coming from a single, effective angle of reverberation. The two dashed lines that bound the data represent Lambert's law for scattering coefficients of -5 and -31 dB/yd^2, as computed from the relation $S = 10 \log (\mu \sin^2 \Theta)$. Values of scattering coefficient estimated from Fig. 12 were compared to mean grain size of the sediment at each station, as listed in Table 3 of Ref. 24. The comparison showed no clear correlation of scattering coefficient with surficial sediment types at the stations represented. These results would indicate then, that from region to region, the scattering coefficient shows a spread of 26 dB, and that this uncertainty does not correlate with sediment type.

Difficulties associated with obtaining valid values of scattering strength are further illustrated by an example cited by Cole and Podeszwa [31]. Experimental data yielded an apparent scattering strength that ranged from -42 to -46 dB/yd^2, based on measured propagation loss values obtained within the water column rather than at the bottom. Post-exercise modeling indicated that the propagation loss at the bottom should be about 6 dB greater than at the 50-ft-deep hydrophone. Hence, the true scattering strength was later estimated at -36 dB/yd^2. The point is that improper experimental techniques can yield improper values of scattering strength.

High frequency reverberation modeling, for frequencies above 20 kHz, generally is based on the scattering strengths given by McKinney and Anderson, shown in Fig. 13 [20]. McKinney and Anderson point out that some sand regions show a backscatter dependence on frequency to the 1.6 power. No such dependence was noted in gravel regions. The results in Fig. 13

apply to 100 kHz, and presumably, the sand curve would be lower at lower frequencies. It is claimed in Ref. 18 however that the McKinney-Anderson frequency dependence is regarded as an isolated case and that there is no basic dependence on frequency.

In summary, numerical techniques of computing reverberation are reasonably well under control. The primary limitation of present ability to predict reverberation is the lack of environmental information. A long range research goal should be to establish a backscatter coefficient data base on a world wide basis for shallow water predictions. A key step that must be made first is to better understand the relevant propagation and scattering mechanisms underlying the reverberation measurements that already have been made. It is not clear whether currently available values of scattering coefficients provide a useful first step toward the generation of the needed data base.

One impediment to the application of the present scientific knowledge to ASW in shallow water is a failing within the research community to understand that the sophisticated scientific research models that have been developed and tested against data are not the same as the models needed for engineering and operational support. Research models have tended to limit themselves to low or mid frequencies and to omnidirectional sources and sensors. Consequently, several aspects of the problem are incomplete in their treatment, aspects such as forward scattering by rough boundaries, doppler smear, and the response of directional sensors. Furthermore, testing of the models against data is often done on the basis of total received power or energy, not on a path by path or arrival by arrival comparison.

A. ENGINEERING SUPPORT MODELS

There is at present no agreed upon standard propagation model for use in shallow water system modeling, but likely candidate models are

SNAP [5] and either NISSM II [21] or one of the selectable propagation models within the Generic Sonar Model (GSM) [32], all of which would need further adaptation and testing. SNAP was developed specifically for shallow water applications and, with its predecessors such as MOATL [33], has played a large role in establishing the scientific base of shallow water propagation. However, like other normal mode models, it has not been incorporated into widely used engineering models as an option for shallow water, primarily because the modal approach is not readily adapted to shipboard sonars (which is a primary application of NISSM II and GSM) and because there has not been a firm commitment at the Claimant level to develop engineering support models for shallow water. NISSM II and GSM are based on ray tracing concepts and already exist as engineering support models. Their validity in shallow water has yet to be established however. Their advantage is that this family of models is widely known and available within the 6.2 and 6.3 communities. Principal specifications for engineering support models, as compared to either scientific or operational models, are that they must be fast and must be robust against variations in input data or against poorly selected computer run control parameters. In addition they must include all relevant environmental effects, empirically if necessary, such as rough surface scattering loss, doppler spreading, vertical arrival structure, and estimates of spatial or temporal coherence.

B. OPERATIONAL SUPPORT MODELS

Most operational models for fleet support do not address shallow water, but some expectation has been expressed that RAYMODE will be able to handle the shallow water environment adequately. Generally speaking, an operational model is used to estimate a gross measure of system performance, such as detection range, and to give guidance for sonar operating mode selection. High accuracy is not necessary, but the models must be robust in their ability to handle a wide variety of environmental conditions with uniform reliability. The major limitation on operational support models is the present lack of a data base for bottom properties.

A key issue that needs to be addressed is whether a shallow water capability for engineering and operational support models is to be established by extension and adaptation of present models or by a new start, building up from the base. Questions to be considered are: How good are present models such as FACT, RAYMODE, Multipath Expansion, and NISSM II when applied to shallow water? and Is it necessary to adapt a model such as SNAP for support applications in shallow water?

V. LONG RANGE GOALS AND BASIC EVA ISSUES

The long range goals listed below are suggested here as appropriate R&D objectives in shallow water propagation for the environmental acoustics community if it is to provide environmental support to the Navy's ASW capability in shallow water:

1) Provide operational support through a capability to predict acoustic ASW performance of systems in shallow water on a world-wide basis.
2) Develop tested guidelines for selection of optimal sonar deployment parameters and operation mode for system use in shallow water.
3) Provide support to engineering design of new systems, or of modifications to present systems, for effective use in shallow water.

These goals represent likely final products from a 6.3 Advanced Development program. Supporting research at the 6.1 level would be designed to provide a basic scientific knowledge of acoustics and of the relevant geophysical environment, as well as quantitative relationships between environment and acoustics. Under 6.2 exploratory development, effort would be directed toward converting the scientific base into products to meet the above goals. Examples of such products might be environmental data base representations, robust and efficient propagation models, and an experimental base of environmental effects on system performance.

Several questions need to be resolved before these goals can be met for shallow water. Many of the questions are of a detailed technical nature that can be answered through continued research and development. Also important, however, are a set of fundamental issues concerning what direction EVA propagation studies should take if they are to provide effective support. The following list identifies some of these larger, fundamental issues, together with some of the technical uncertainties that would need to be reduced if the issues are to be properly resolved.

<u>ISSUE 1</u>. Is the present understanding and modeling of shallow water acoustics, at the basic scientific level, sufficiently advanced to permit the development of either operational or engineering support models.

Present knowledge of shallow water propagation, and techniques to model it, are highly sophisticated. Technical uncertainties that need to be addressed include:

- o how important is shear in sediments
- o what is the frequency dependence of compressional wave absorption in sediments
- o how significant are the influences of rough boundaries on losses in signal energy and coherence

- o are signal and noise vertical directionality adequately modeled at present
- o what are the relative contributions of bottom roughness and subbottom inhomogeneities to reverberation.

<u>ISSUE 2</u>. Can useful EVA performance prediction support be given to tactical system design or to tactical system deployment in shallow water on the basis of models that do not address lateral variability of the environment.

Related technical questions are what levels of prediction accuracy are attainable in shallow water, and what accuracy is needed for predictions to be useful.

<u>ISSUE 3</u>. Can useful acoustic forecasts for a region whose acoustic properties have not previously been measured, be made on the basis of geological similarity to a known region, without the need to make any acoustic measurements in the region in question.

A related technical question is:

- o Can adequate estimates of bottom loss and backscatter coefficient be made solely on the basis of generally available information such as sediment type.

<u>ISSUE 4</u>. Can an adequate data base of bottom parameters be developed to support world-wide shallow water ASW performance prediction.

This issue rests on the sub-questions:

- o What is the minimal set of bottom parameters needed to provide an adequate prediction capability.
- o How does this minimal set depend on generic system properties.

- o How are separate EVA parameters correlated. What, for example, is the relation between backscattering strength and other parameters such as sediment type, bottom roughness, bottom loss, sub-bottom layering.
- o Can practical broad-area surveys produce the needed data base.
- o What survey techniques are needed to support prediction of initial detection range and determination of whether detections are against reverberation or noise.
- o What spatial resolution is needed.
- o Can a data base of backscattering coefficients be based either on sediment type or on geographical location.

VI. RECOMMENDED RESEARCH EFFORTS

The long range goals identified in the previous section can be realized through a systematic research and development program such as the one outlined below. Ideas generated at a recent ONR workshop [34], held to formulate goals and a tentative program for shallow water acoustics at the 6.1 basic research level, are included here. The program is directed toward shallow water propagation, reverberation, and coherence, as related to ASW, and does not address other research needs such as noise or system design. The program also has included in a general way many of the present efforts already in effect, and it is not intended to imply that all aspects of the program are new or original.

BASIC RESEARCH

1. Identify through experiment and analysis the fundamental environmental parameters of the ocean bottom that control acoustic losses, and establish quantitative relations between measurable parameters and propagation loss. Parameters considered should include shear properties, depth and

frequency dependence of compressional absorption, sediment thickness, sediment layering, and boundary roughness.

a. Identify and test techniques for efficient measurement of the parameters identified in item 1.

b. Determine global extent and rate of lateral variability of key parameters.

2. Examine techniques for three-dimensional propagation modeling.

3. Establish quantitative relations between rough boundaries (at surface or bottom) and such effects as forward and backward scattering, out-of-plane scattering, azimuthal spreading, coherence, and frequency spreading.

a. Relate these effects to various roughness descriptors such as rms roughness or roughness spectrum.

b. Establish relations between surface wave spectrum, windspeed, and scattered field, including the effects of near-surface bubbles.

c. Examine the relative scattering contribution by inhomogeneous structure within the sediment.

4. Establish a systematic framework relating time series, spectra and correlation as a basis for reviewing existing coherence data.

EXPLORATORY DEVELOPMENT

5. Develop candidate environmental data bases, along with extrapolation techniques and resolution requirements that would support world-wide acoustic predictions in shallow water.

a. Develop survey techniques for the measurement and processing of data to yield values of bottom loss and backscatter coefficient.

b. Establish an empirical relationship between backscatter coefficient and sediment type in order to test the concept that backscatter can be estimated on basis of sediment type alone.

6. Develop engineering submodels for coherence, fluctuations, rough boundary effects, reverberation spectrum, moving platform effects, and lateral variability of the environment.

7. Conduct experiments that delineate environmental influences on system performance, and test techniques to exploit the environment.

   a. Develop techniques to use on-site measurements of reverberation in an operational context.

8. Develop inversion techniques that would allow estimation of target depth, bearing and speed, based on received signal structure, coupled with a knowledge of shallow water propagation characteristics.

9. Develop active sonar transmitting waveforms that optimize ability to suppress reverberation in shallow water and determine world wide applicability of candidate waveforms.

10. Develop signal processing algorithms and display techniques that best distinguish targets from other sources of return.

ADVANCED DEVELOPMENT

11. Evaluate and implement model components and data bases for shallow water operational models used in acoustic forecasting.

12. Conduct follow-up development of advantageous design or deployment techniques identified in 6.2 efforts.

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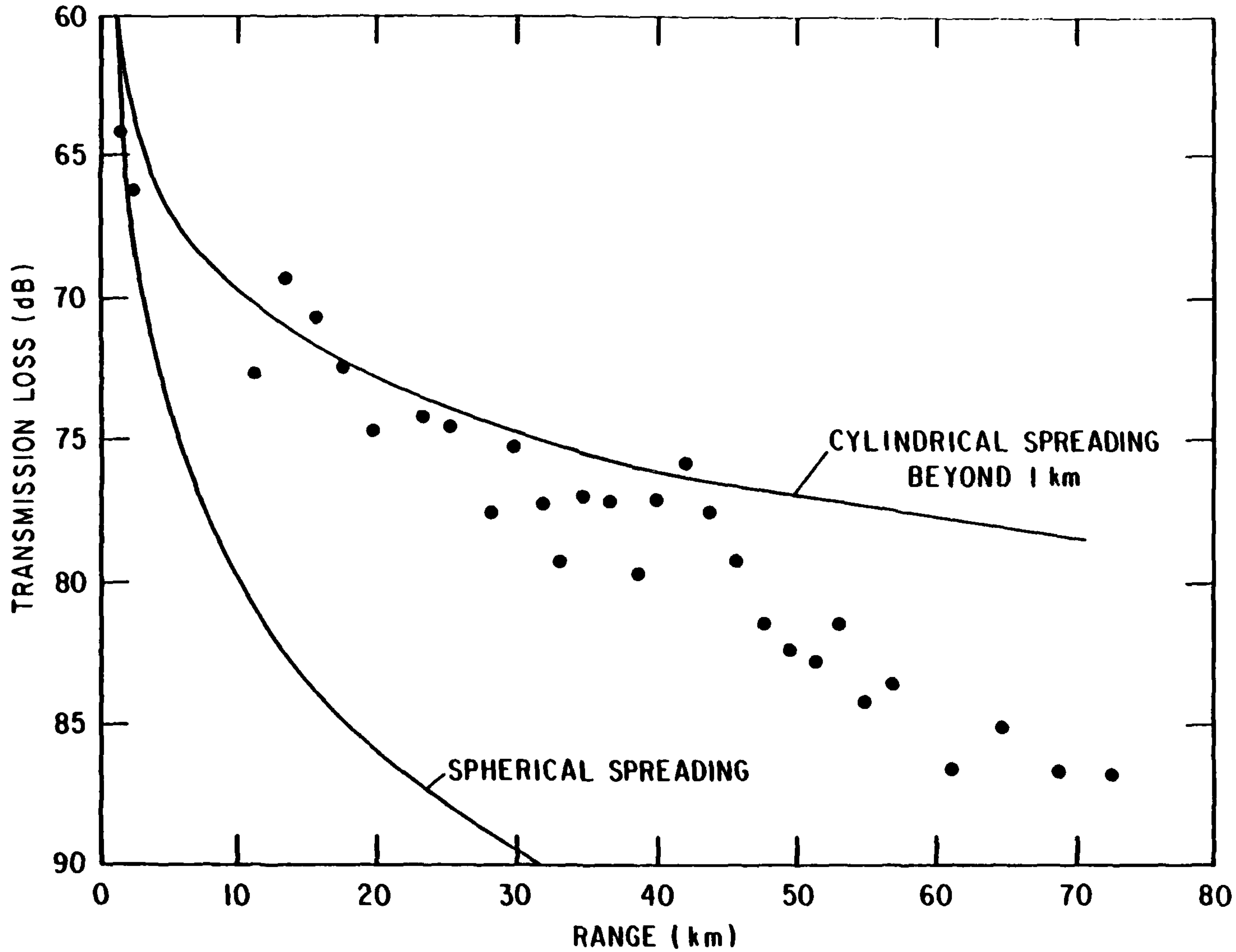

Figure 1. Example of one-third octave propagation loss data at 200 Hz in shallow water illustrating the cylindrical spreading that results from trapping energy in the waveguide.

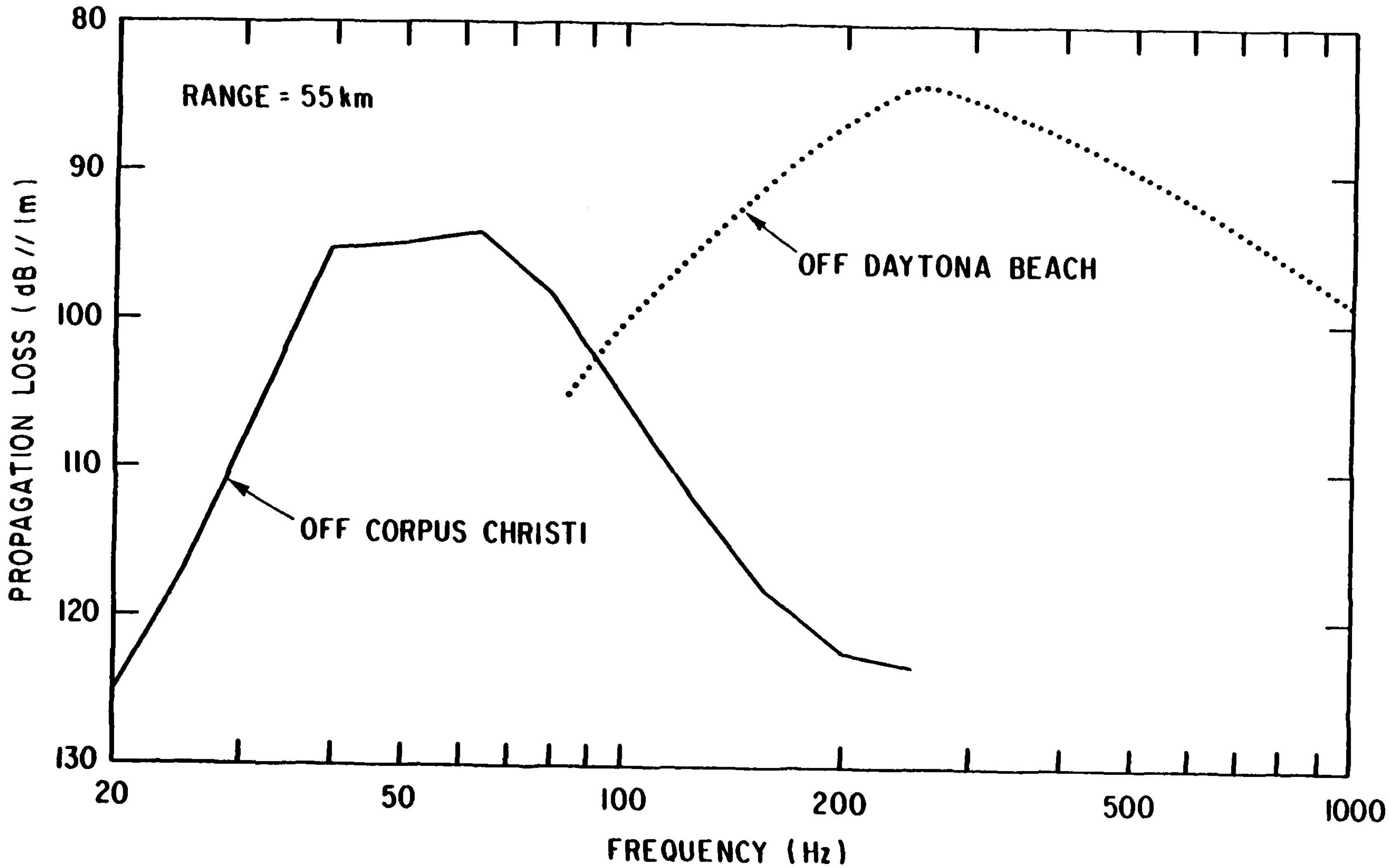

Figure 2. Comparison of propagation loss spectra at two locations.

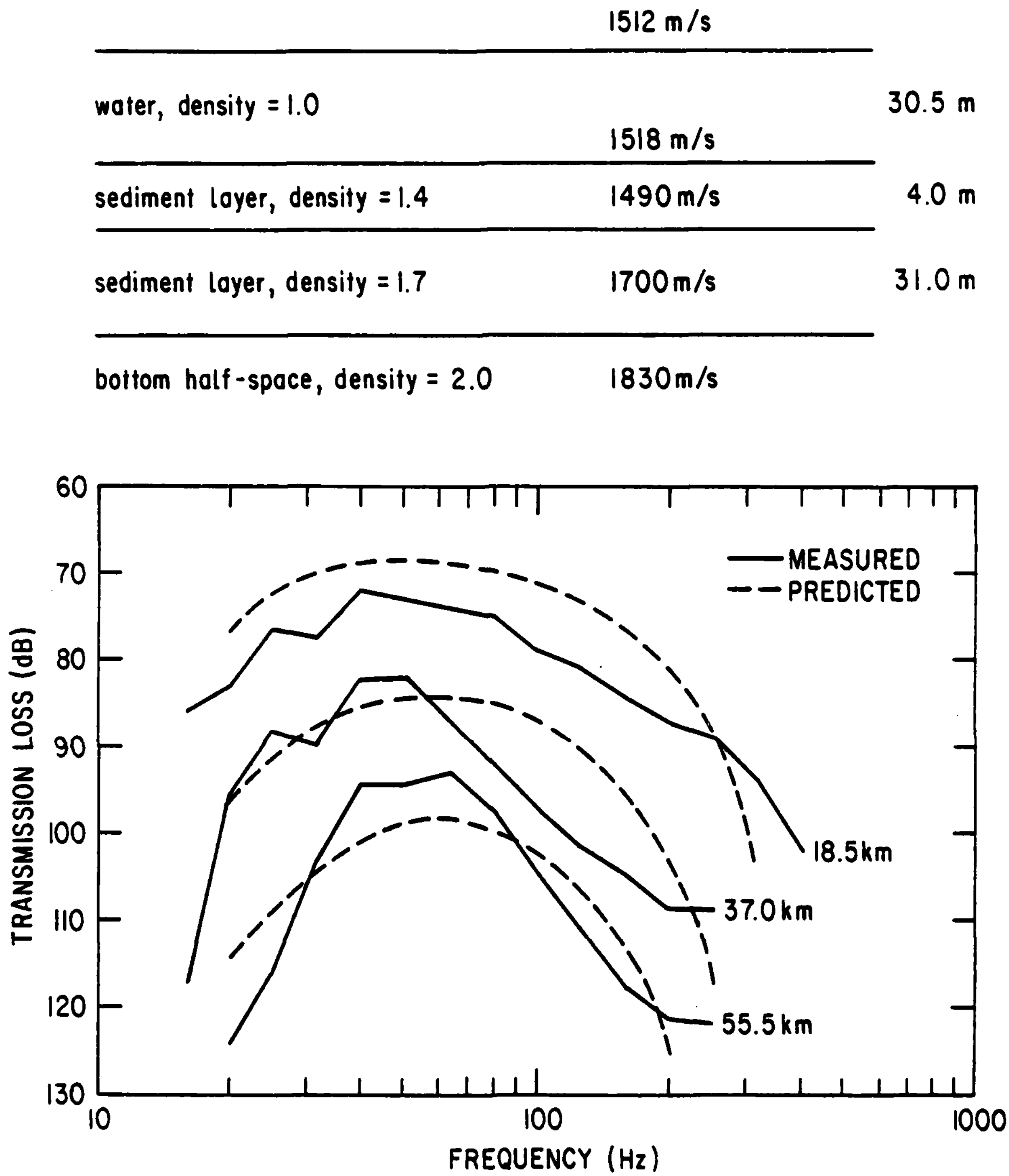

Figure 3. Geoacoustic model of the experimental region (top) and measured and predicted transmission spectra at three ranges (bottom) for a region with a slow sediment layer. [From Ref. 2]

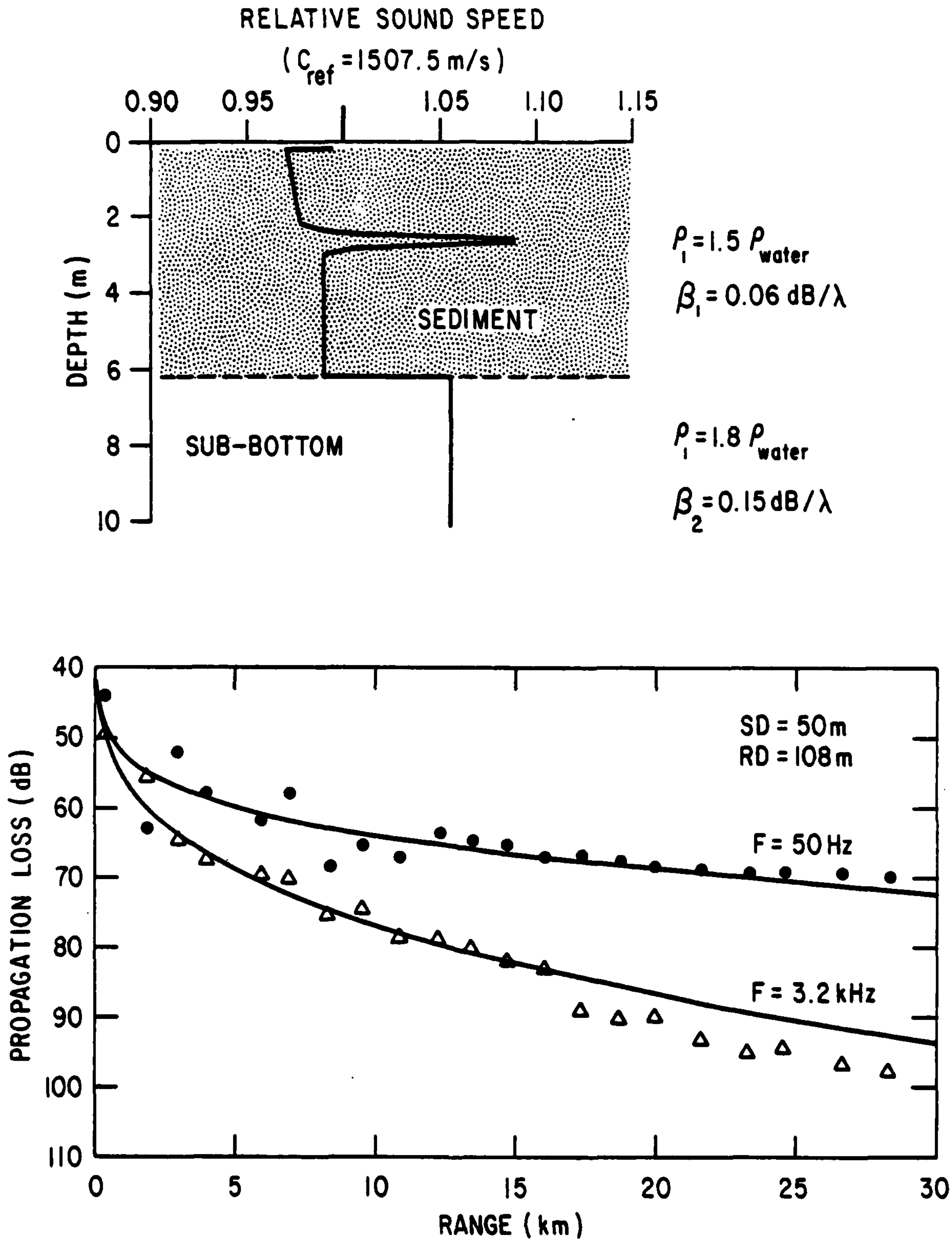

Figure 4. The geoacoustic model (top) and measured and predicted propagation loss against range (bottom) for a region with a slow sediment layer [From Ref. 5].

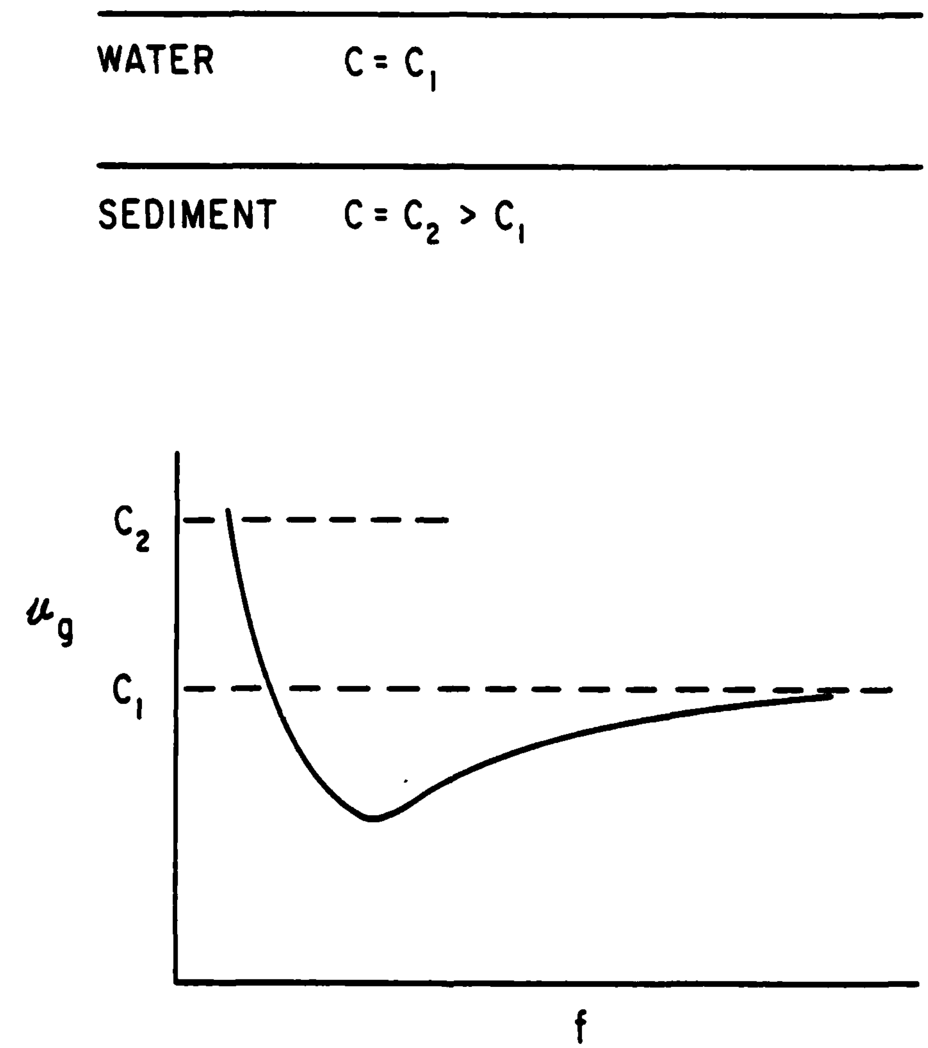

Figure 5. Environmental model (top) for fast sediment in shallow water and corresponding dispersion curve for a single mode (bottom).

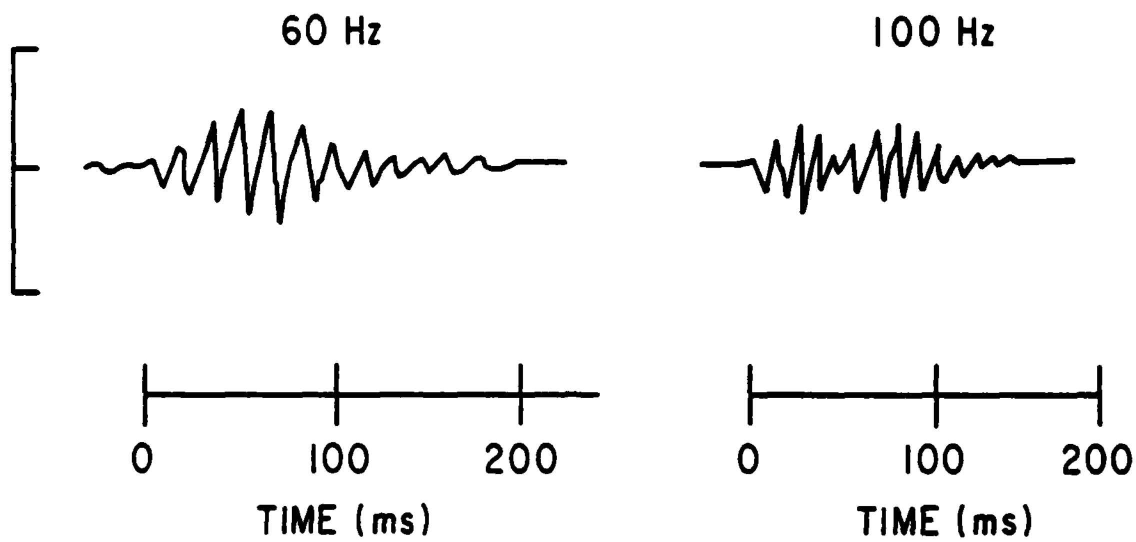

Figure 6. Time stretching of an initial four-cycle pulse due to dispersion and multiple arrivals in shallow water.

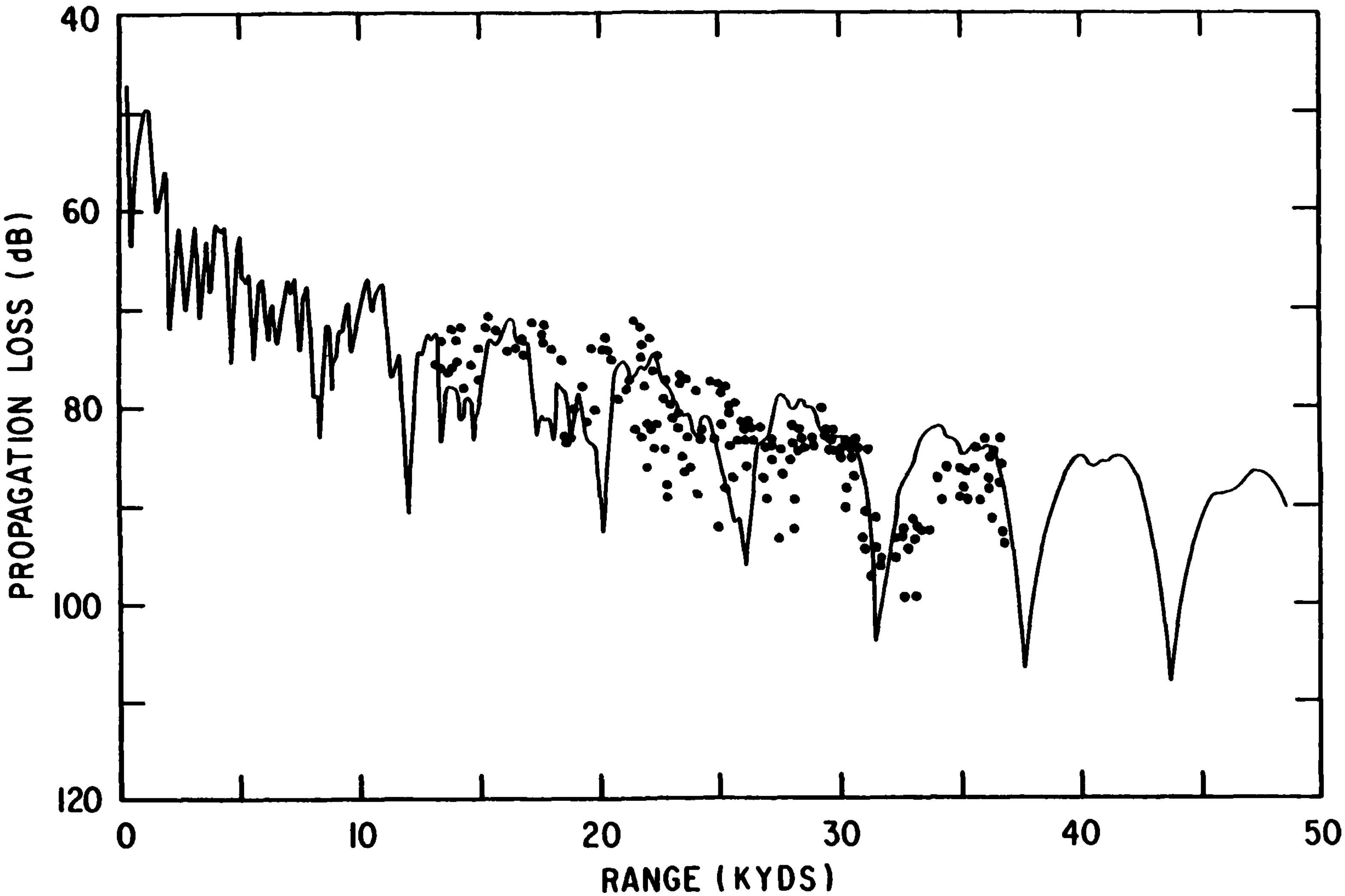

Figure 7. Propagation loss data points and predicted curve in shallow water. [From Ref. 16]

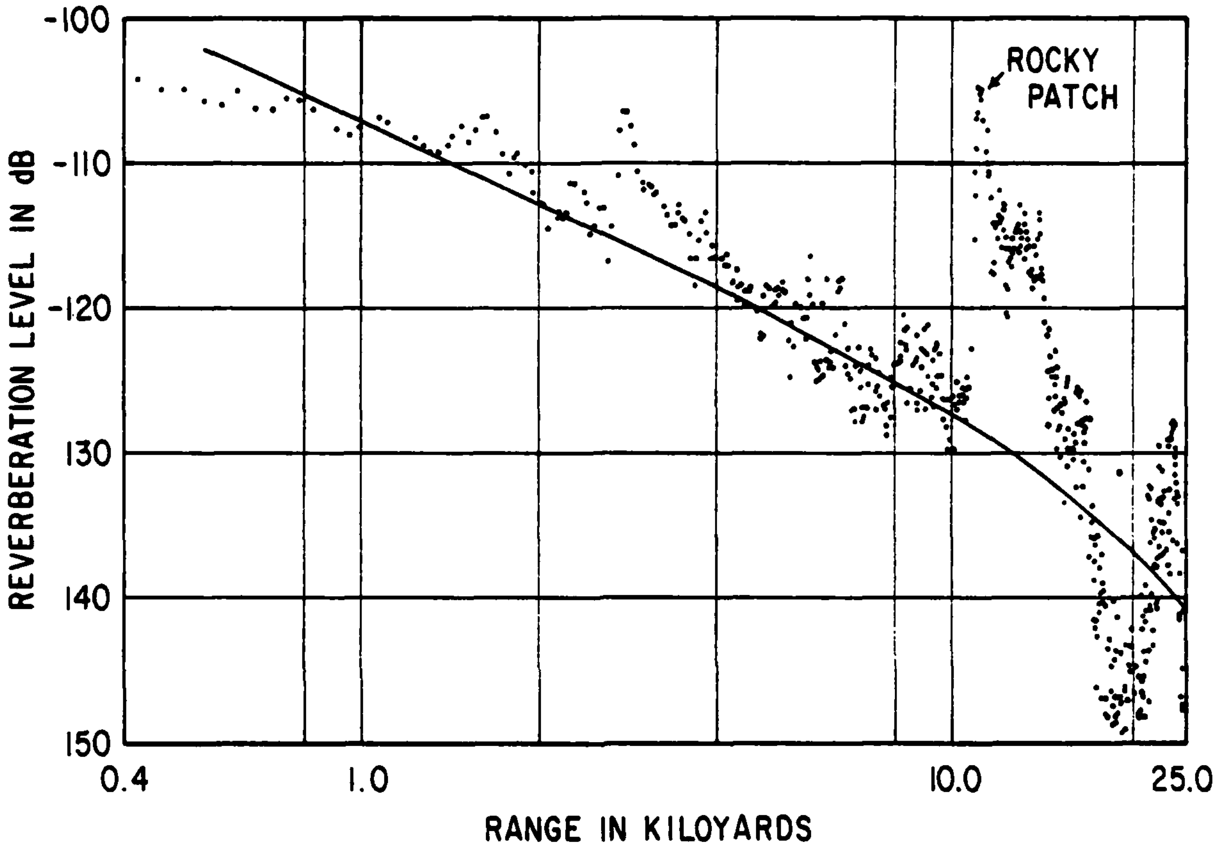

Figure 8. Reverberation level vs. range for 700-c/s sound at Pigeon Point Shelf, point D, with beam heading 072°T, to show the rocky patch, as indicated in Fig. 9 [From Ref. 23].

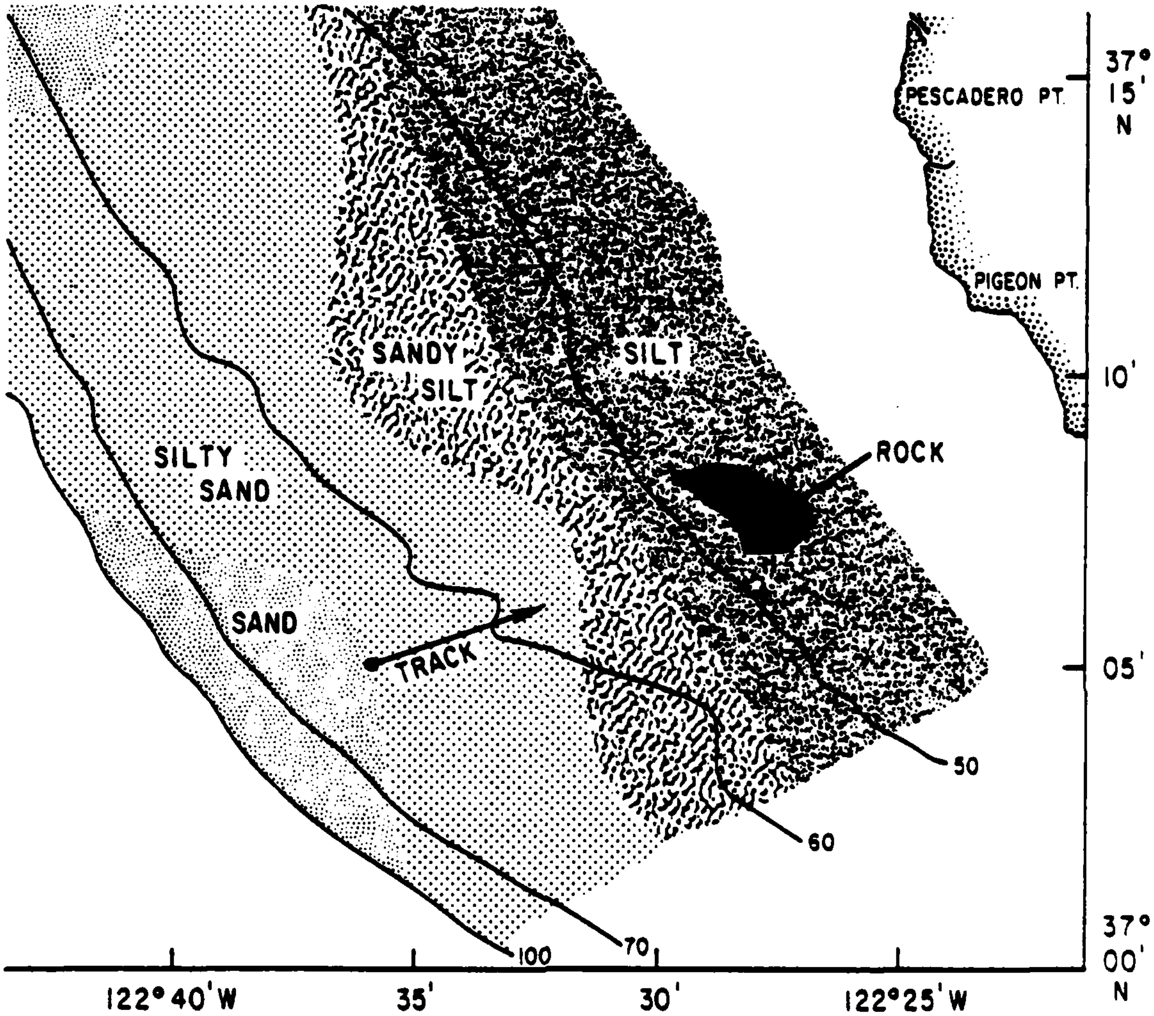

Figure 9. Sediment distribution and bathymetry (in fathoms) for reverberation measurement at Pigeon Point Shelf near San Francisco.

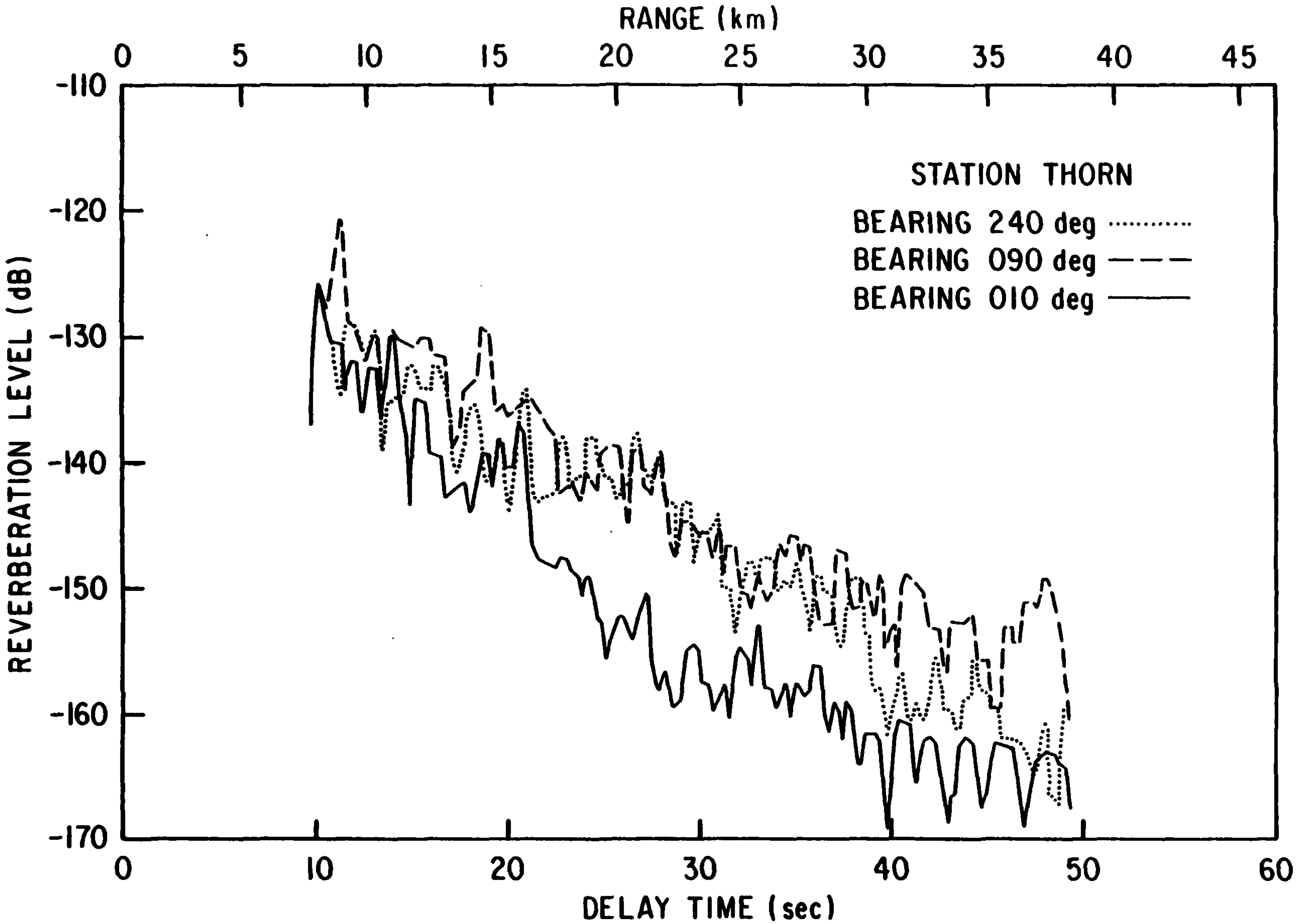

Figure 10. Reverberation against range at three bearing angles. Frequency 1500 Hz, pulse length 0.5 sec [From Ref. 24].

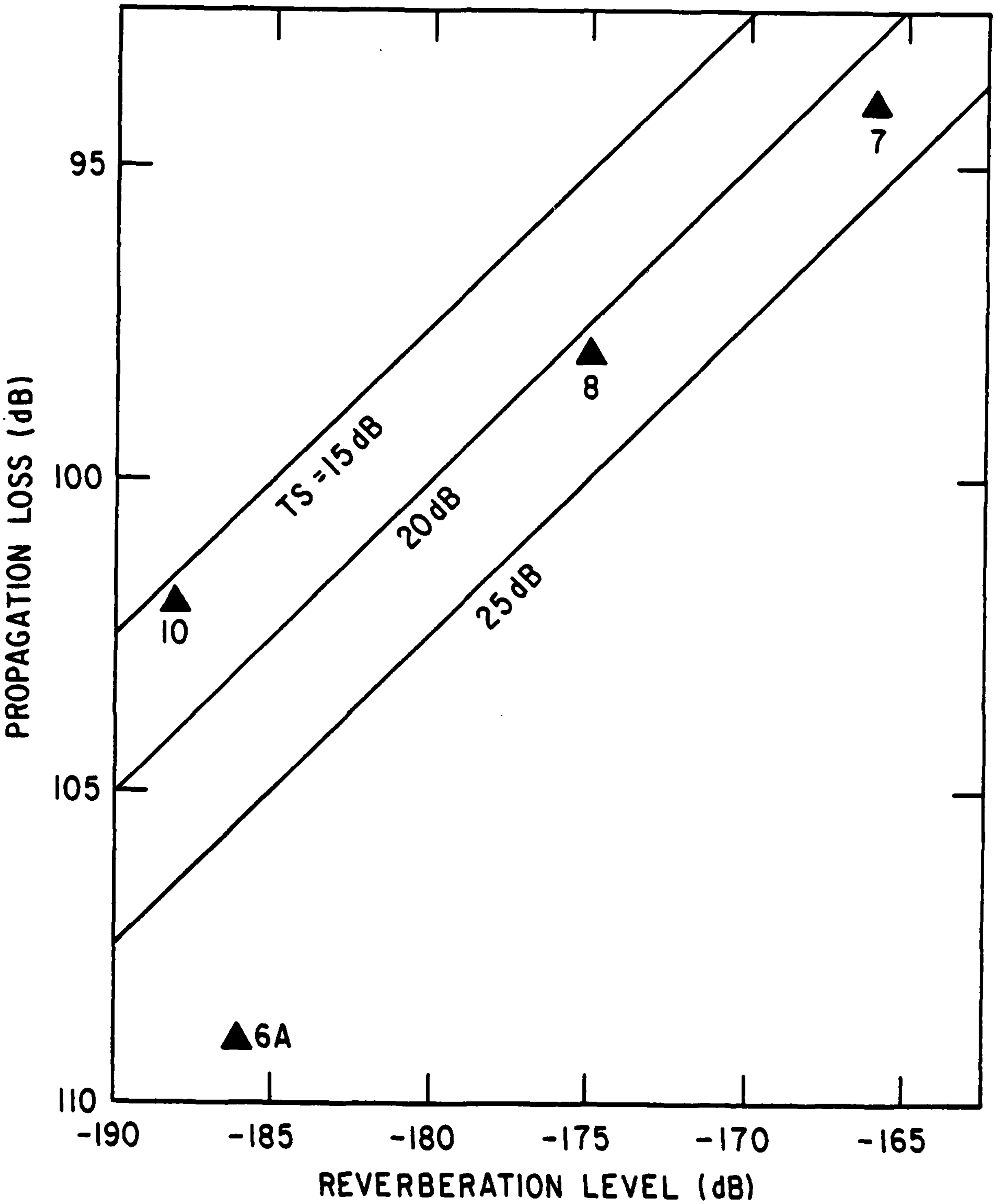

Figure 11. Correlation of reverberation and propagation loss.

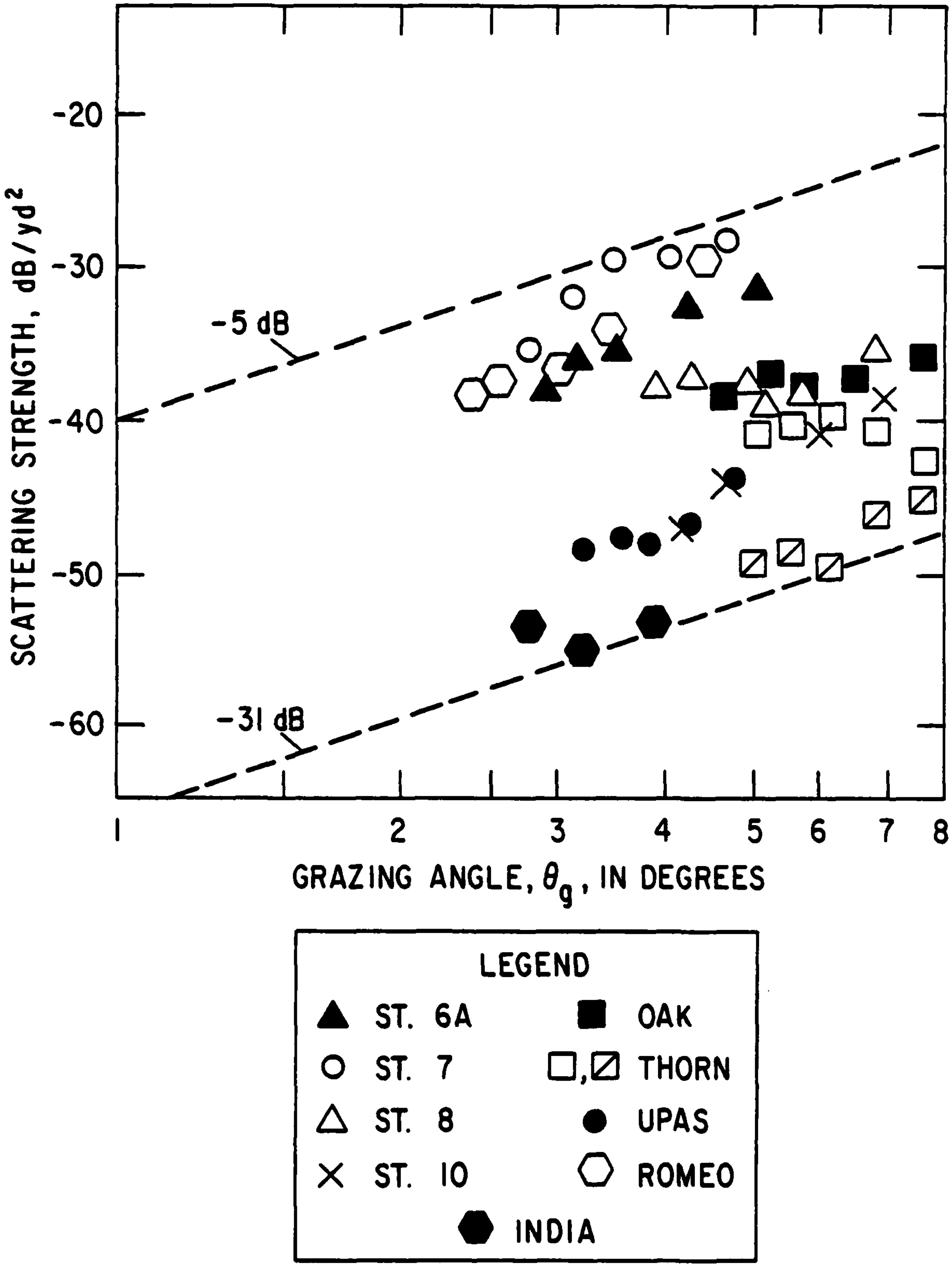

Figure 12. Scattering strength as a function of grazing angle.

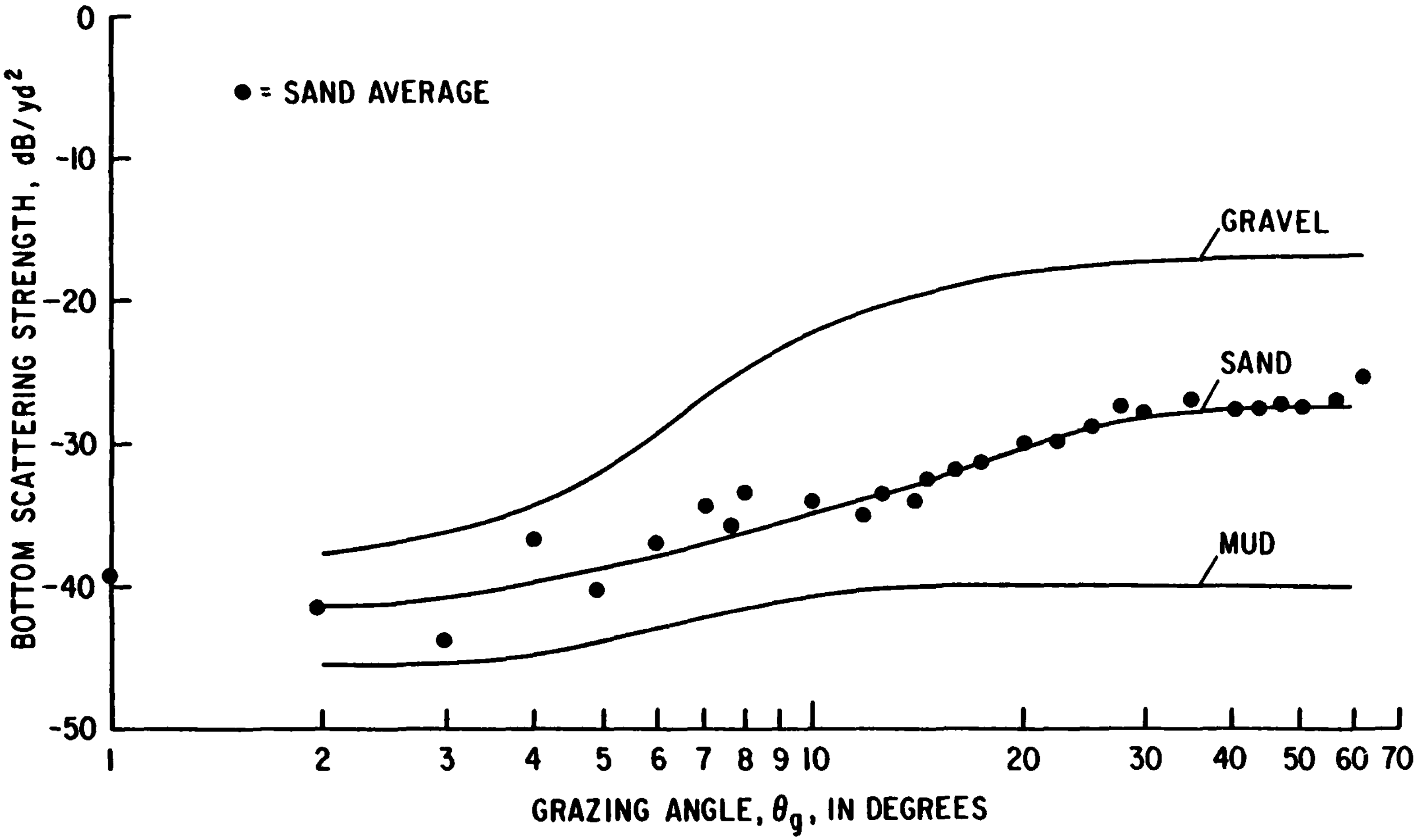

Figure 13. Average curves for bottom-backscattering strength S_B as a function of grazing angle θ_g [From Ref.20].